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Comparison of hydrogen internal combustion engines and hydrogen fuel cell engines for true zero-emission heavy-duty fleets

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Introduction

As the largest contributor to greenhouse gas emissions in the transport industry, the road transport sector – including emission-intensive freight and logistics operations – is facing several challenges in switching operations to zero-emission technologies.

As these businesses seek commercially viable pathways to meet decarbonization targets, the debate between adopting hydrogen internal combustion engines (H2ICE) and hydrogen fuel cells has recently emerged as complex and multifaceted - both contingent on short-term vs. long-term views.

The crux of the matter is not just the technological capabilities of these two hydrogen-based solutions, but also their compatibility with the overarching goal of reducing carbon emissions in sectors that are both cost-sensitive and operationally demanding. Hydrogen, with its high energy density and no carbon content, presents a promising route to achieve zero emissions.

However, integrating hydrogen technology into heavy-duty vehicles involves a wider set of challenges, including infrastructure development, energy efficiency, capital cost and total cost of ownership.

H2ICE, on one hand, are viewed by some as a simpler transition from traditional diesel engines, potentially leveraging existing engine and powertrain designs. This perceived compatibility suggests a lower upfront cost and simpler integration into current vehicle fleets. Hydrogen fuel cell engines, on the other hand, are viewed as more efficient and cleaner in terms of emissions but seen as requiring significant changes in vehicle design and higher initial capital investment.

As both technologies require a new hydrogen refueling infrastructure, the scale up of hydrogen production from renewable sources and availability are also key considerations.

For road transport and logistics firms, which tend to operate on tight margins, fuel is the highest operational cost. Fuel consumption – and therefore engine efficiency – is of paramount importance, especially for long-distance freight operators.

POLICY CONTEXT

GOVERNMENTS IN NORTH AMERICA AND EUROPE ARE SETTING AMBITIOUS TARGETS FOR ZERO-EMISSION HEAVY-DUTY VEHICLES TO COMBAT CLIMATE CHANGE. IN CALIFORNIA, THE CLEAN TRUCKS PLAN MANDATES STRINGENT EMISSIONS STANDARDS FOR MODEL YEARS 2027-2032. SIMILARLY, THE EUROPEAN UNION TARGETS ALL NEW HEAVY-DUTY VEHICLES TO BE ZERO-EMISSION BY 2040, WITH INTERIM TARGETS SET FOR 2030 AND 2035.

Purpose of the paper

This paper examines and compares direct hydrogen injection combustion engines and fuel cell engines, focusing on their respective future costs. This paper is not looking at dual fuel (H2 and diesel) ICE as it does not meet zero-emission regulations. The purpose is to provide a comprehensive analysis that supports decision-making regarding the most suitable technology for road transport, freight and logistics applications, considering operational criteria.

Scope

Hydrogen fuel cells and H2ICE for medium- and heavy-duty truck applications are within the scope of this analysis.

H2ICE and fuel cell engine technology introduction, characteristics, limitations and challenges

H2ICE and fuel cell engines both utilize hydrogen as fuel but they differ in how this energy-dense fuel is converted to power for the vehicle. Both engines require storage and delivery systems for hydrogen onboard the vehicle and the operating pressure of these storage systems will likely be the same for fuel cell and H2ICE vehicles. There can, however, be small differences in tank capacity requirements due to the different fuel consumption efficiencies between the technologies.

As electrochemical power generators, fuel cell engines are very efficient as they directly convert chemical energy into electricity. As such, fuel cells generate electricity to directly power the energy efficient electric drivetrain and have demonstrated typical efficiency of 48-58% in operation.

Internal combustion engines, including diesel, natural gas and hydrogen fuels, have lower efficiency due to the physics of converting chemical energy into mechanical energy.

The full difference between fuel cells and H2ICE is still open to discussion due to the early development stage of H2ICE technology and lack of actual road data. However, based on the laws of physics, fuel cell electric vehicles will always be more efficient than H2ICE, especially as an electric vehicle provides the opportunity to regenerate braking energy. This is a significant advantage for fuel cell vehicles due to their higher drive cycle efficiency.

H2ICE

A H2ICE converts chemical energy in hydrogen fuel to kinetic energy which, in this context, is a rotating mechanical shaft connected to the vehicle drivetrain. The H2ICE is much like a conventional combustion engine: it contains a block, crank shaft, pistons, cylinder heads, spark ignition (typically), cam shafts and valve system, fuel delivery, air intake, lubrication, cooling, exhaust after-treatment, pumps, timing systems, sensors and actuators.

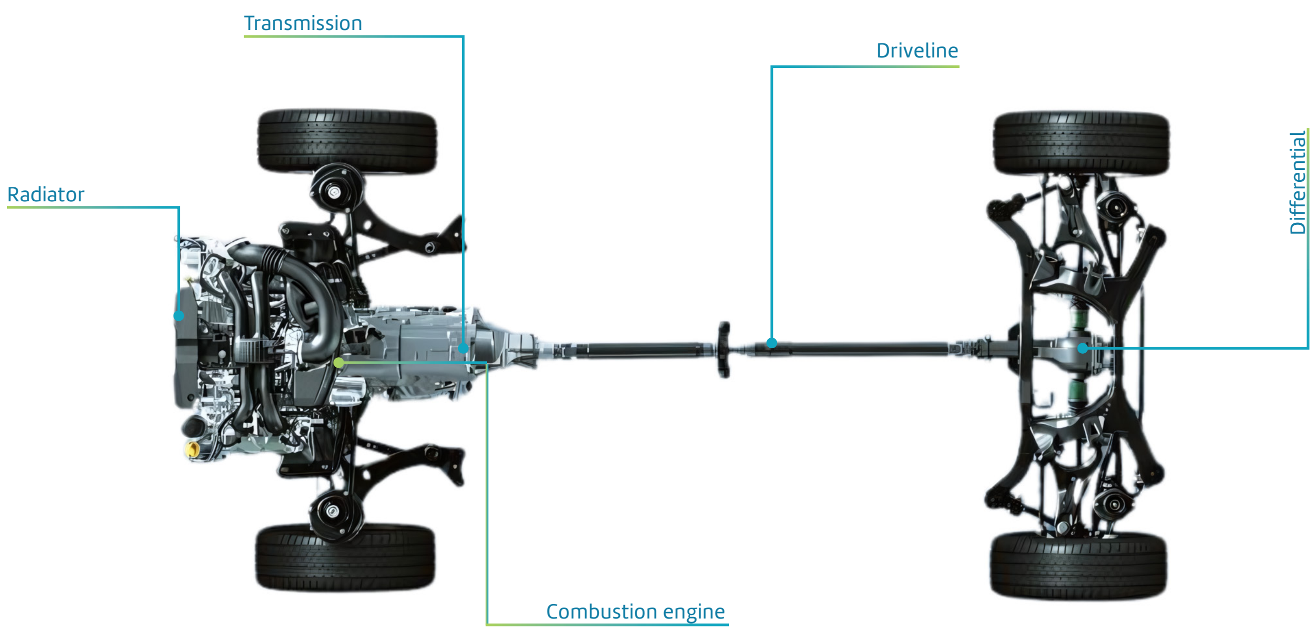
Many of the components and systems within the H2ICE are high-performance and complex, and more than 100 years of maturation and high production volumes enable relatively low cost. This accomplishment is supported by advanced manufacturing value chains to achieve extraordinary results. A modern combustion engine is a demonstration of what can be accomplished from decades of focused development of technology, materials, integration, know-how, and manufacturing processes.

Although diesel and gasoline combustion engines are mature technologies, H2ICE innovation is still undergoing research and development efforts, focusing on fuel and air delivery, combustion, ignition, thermal management, lubricants, durability, management of emissions - and development of materials that are both compatible with hydrogen and suitable for high temperature combustion[1].

A H2ICE requires an exhaust after-treatment system since the engine will emit greenhouse gases, NOx and possible particulate matter from engine lubricants.

In the vehicle, a H2ICE could be integrated with batteries into a hybrid powertrain, but the prevailing expectation is that the H2ICE will be fitted with the same drivetrain as a conventional combustion engine.

H2ICE Powertrain



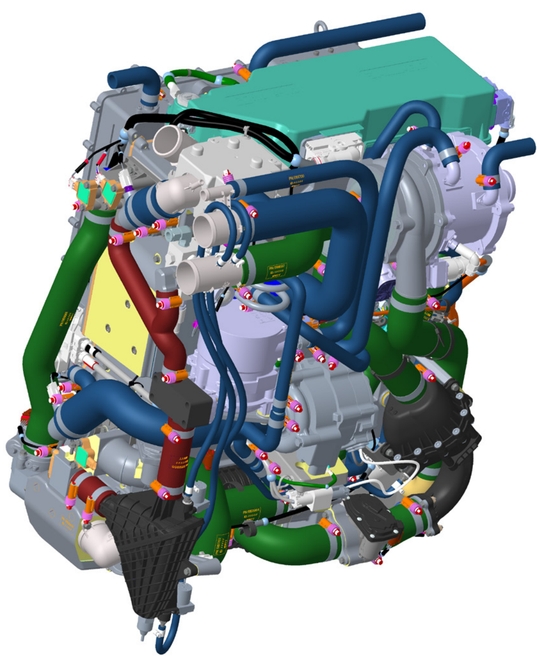
[1] https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/C-pdf.pdf

H2ICE APPLICATIONS

Current expectations are that H2ICE could be well-suited to retrofit vehicles and applications in industries with high vibration and dust-laden air, such as agriculture and construction. Other examples include vehicles where fuel efficiency is not the most important factor, such as fire and rescue services[2].

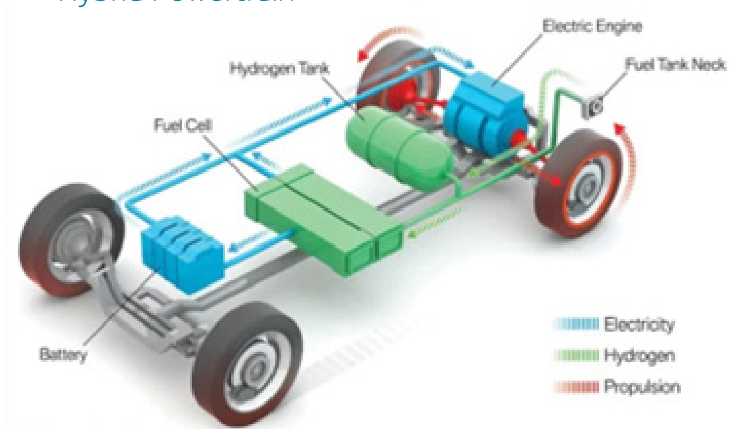
FUEL CELL ENGINE DESCRIPTION

Transportation applications in the scope of this examination utilize proton exchange membrane (PEM) fuel cell technology. A PEM fuel cell engine converts chemical energy in hydrogen fuel into electricity which, in this context, powers an electric drive motor to propel the vehicle. The fuel cell engine contains a fuel cell stack, fuel delivery system, air intake, cooling, sensors and actuators, a DC/DC converter, and a control system.



A fuel cell vehicle is an electric vehicle. The fuel cell engine integrates with a battery, or other energy storage device, into an electric drivetrain to form a hybrid powertrain to propel the vehicle, capture regenerative energy, and power vehicle auxiliary systems (lights, heating and air conditioning, electronics, etc.)

Hybrid Powertrain



In this hybrid powertrain, the fuel cell and battery both contribute to vehicle propulsion with the possibility to specify different ratios of fuel cell-to-battery power to achieve the desired vehicle performance objectives. Often, the fuel cell supplies the average power required for vehicle operation, while the batteries provide the power needed for transient loads such as acceleration. In this hybrid configuration, the required number of battery packs is less than a battery-only vehicle since hydrogen – not batteries – is supplying the energy for the drive cycle.

The torque, efficiency, and performance characteristics of electric powertrains are well known[3] and, along with cost and maintenance advantages, contribute to a strong business case for adoption and use of fuel cell electric powertrains as a preferred solution for many heavy-duty commercial applications[4].

[2] https://www.energy.gov/sites/default/files/2023-03/h2iqhour-02222023.pdf
[3] https://afdc.energy.gov/fuels/electricity-benefits
[4] https://www.nrel.gov/docs/fy21osti/71796.pdf

Vehicle integration concepts

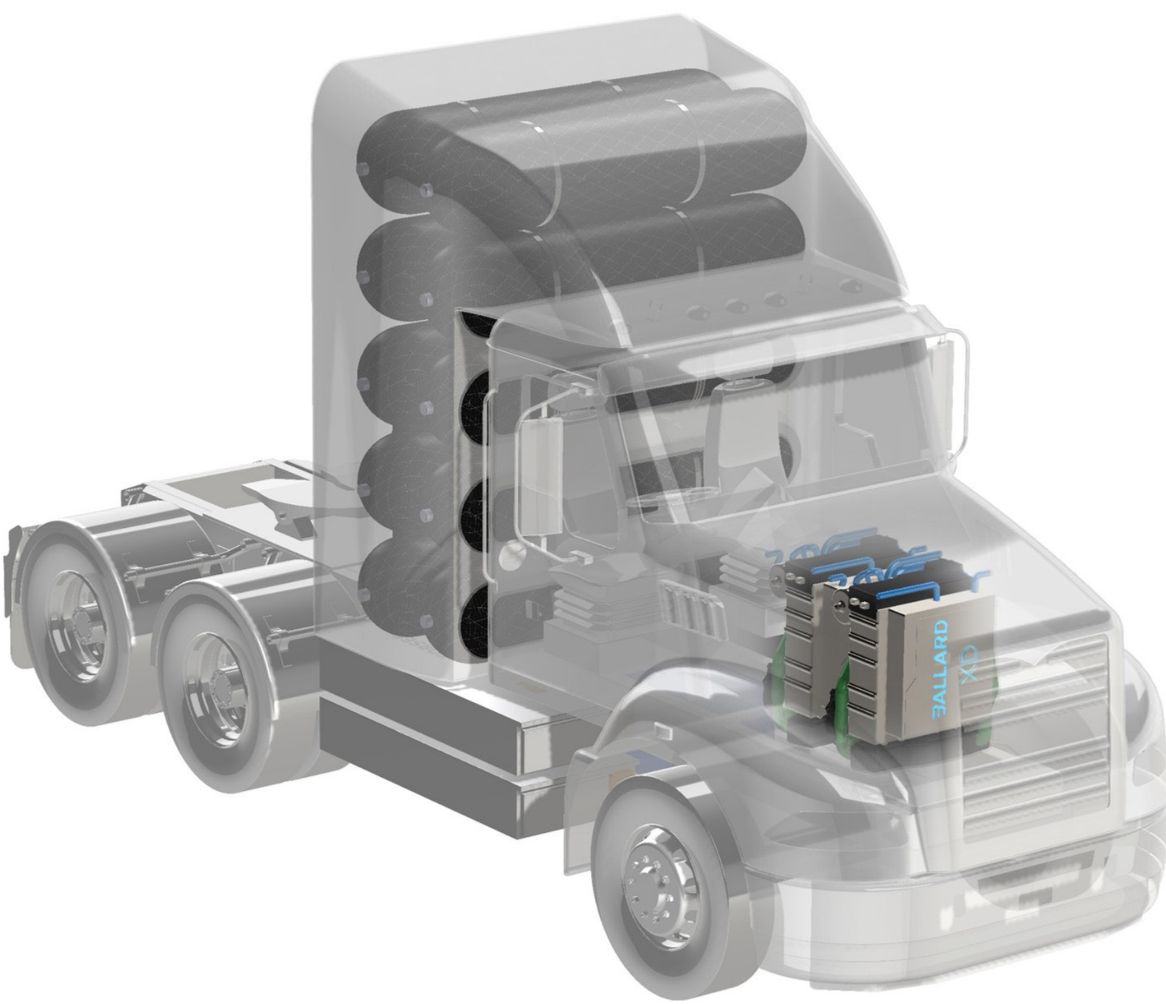
H2ICE VEHICLE INTEGRATION

The H2ICE integrates into a conventional drivetrain consisting of transmission (gear box), drive shaft(s), rear differential (final reduction), and axles. A typical diesel heavy-duty truck consumes approximately 33 liters per 100 kilometers. Assuming the H2ICE achieves a 5% efficiency improvement, the expected fuel consumption would range from 10-12 kg/100km.

FUEL CELL VEHICLE INTEGRATION

It's convenient to think of a fuel cell hybrid vehicle as simply a battery vehicle with the addition of a fuel cell engine, hydrogen storage and increased cooling, with a substantial reduction in the number of battery packs and their associated weight. The typical fuel consumption of a heavy-duty fuel cell truck is in the range of 8-10kg per 100 kilometers.

Efficiency and fuel consumption varies based on vehicle type, drive cycle and driver behavior, but in all cases a fuel cell electric truck will always be more efficient than a H2ICE with transmission. Hydrogen fuel consumption of a H2ICE truck will always be higher than a fuel cell electric vehicle.



ENGINE TECHNOLOGY COMPARISON

There are some known issues with the combustion of hydrogen. Hydrogen combustion is less heat conductive than natural gas combustion (no carbon low mass for heat transportation) as CO_2 conducts three times more heat than a hydrogen air mix, leading to a compromise in heat conduction for large piston diameter engines and concentrated heat points. The loss of power and torque needs to be compensated by larger engine displacement.

There are also several unknown factors regarding the durability and maintenance cost of H2ICE regarding the lifetime of fuel injectors, lubricants, after treatment (high H_2O on the exhaust), impact of hydrogen embrittlement of metallic components and oxidation due to H_2O production. There are still engineering challenges to solve before commercialization at scale. The most significant of these are precombustion and the limited injector lifetime due to lack of lubrication (limited to 1,000hrs today). (1)

COMPARISON WITH DIESEL ICE	FCE	SCORE	H2ICE	SCORE
Cooling	More radiators due to lower coolant temperature	Not as good	More heat to reject (lower efficiency) but same radiator	Equal to
Drivetrain	Few mechanical losses, higher performance (torque), less fluids, few moving parts, regenerative brake energy	Better than	No difference	Equal to
H2 Tank	Higher volume for same range	Not as good	Even higher volume for same range	Much worse
Engine	Few moving parts, no lubricants, similar power density, higher specific power	Better than	Combustion (Otto cycle), lubricants, moving parts, lower power density	Not as good
Efficiency	Higher efficiency	Better than	Equal efficiency	Equal to
Lubricants	Zero	Better than	No difference	Equal to
NOx	Zero	Better than	Lower than diesel but after treatment required	Equal to
CO_2	Zero	Better than	Much lower	Better than
PM	Zero	Better than	Possible (from lubricants)	Equal to
Noise	Quieter for FCE	Better than	Noisier for H2ICE	Not as good
Maturity	TRL 8 -9 large fleet deployments	Not as good	TRL 6-7 – demonstration vehicles	Much worse
Cost	-- Refer to Cost Comparison (below) --			

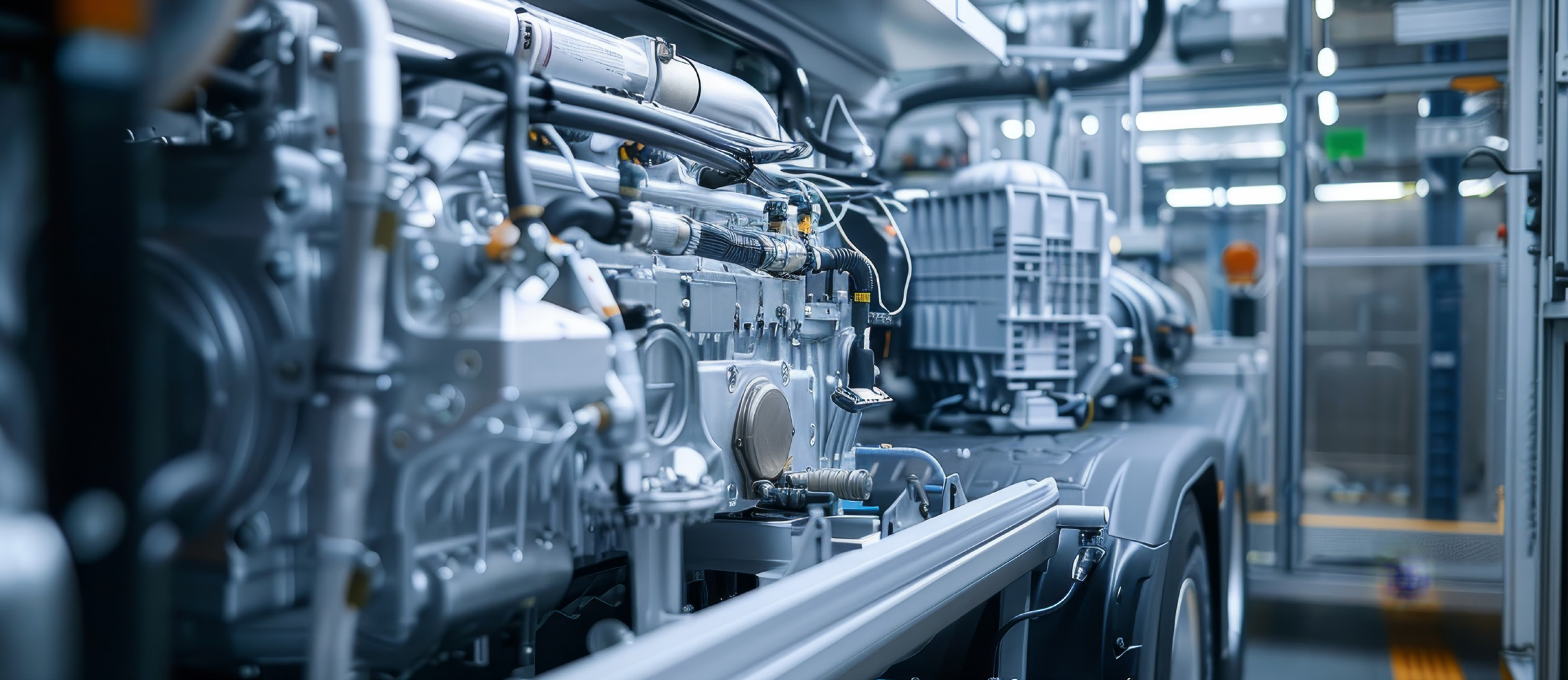
Legend, compared to diesel	Better than	Equal to	Not as good	Much worse

Compared to the H2ICE powertrain, the advantages of the fuel cell electric hybrid architecture include true zero emissions, a more efficient drivetrain, and higher fuel efficiency resulting in reduced fuel storage and longer range between fueling events.

Currently, fuel cell engines are higher cost than diesel engines, but cost continues to decline as technology and designs mature, capital investments in manufacturing are made, and volumes increase. The cost of H2ICE is not yet published but is likely to be higher than diesel for the same reasons as natural gas engines: even after 30 years of development [5], costs are higher than diesel engines[6].

The future cost reduction possibilities of fuel cell engines and H2ICE are explored in the remainder of this paper. We investigate the cost potential of the different solutions by comparing the respective subsystems, focusing on components, construction material, and operation of each.

[5] https://www.cummins.com/news/2023/09/19/total-cost-using-natural-gas-engines
[6] https://www.freightliner.com/blog-and-newsletters/natural-gas-trucks-vs-diesel-trucks/



COMPLEXITY IS COST

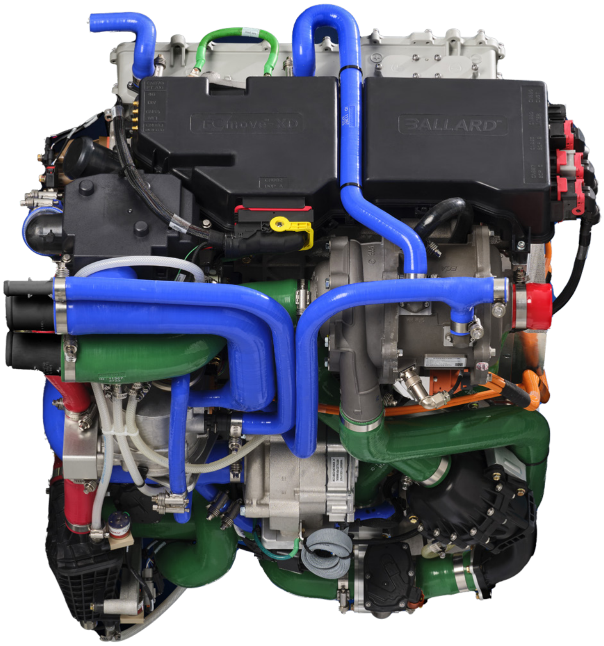
– and fuel cell engines are less complex than ICEs

Fuel cell engines operate at low temperature (<100°C) and low pressure. In contrast, H2ICE operate at higher temperatures than CNG or diesel engines. The impact of hydrogen on metal, and possible oxidation due to water, require more robust materials than fuel cell engines.

A fuel cell engine is much simpler than any internal combustion engine, comprising 20–30% fewer parts than an ICE.

Fuel cell engines do not require any after treatments – which can often be complex. They are true zero-emission with only water vapor emitted.

To assess the future cost of both technologies, it is important to consider the differences in the main components of both engine technologies.

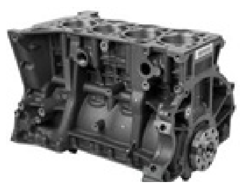
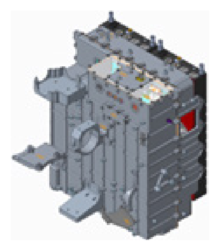
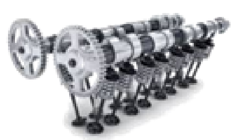


A fuel cell engine integrates five simple subsystems:

1. **Enclosed stack assembly:** Fuel cell stack, enclosure, DC/DC converter, ECU/RDU, software, LV/HV power distribution board
2. **Hydrogen system:** H2 pre-heater, H2 valves, *H2 recirculation blower*, water separator and P/T sensors
3. **Air systems:** *air compressor*, aftercooler, P/T sensors, humidifier, water separator and air valves and mass flow meter
4. **Coolant system:** water valves, P/T sensors and coolant pump
5. **Wiring harness and hose connections**

Only three major components with moving parts

MAJOR COMPONENT COMPARISON

ICE		FCE	
Large number of parts with complex manufacturing processes and precision. High level of mechanical and thermal stress leading to the use of special materials and thermal treatment. Need cooling and lubrication systems to operate properly. High mechanical losses	Produced rotational (kinetic) motion 	Low number of parts with automated manufacturing process. No mechanical or thermal stress. High efficiency of energy conversion. Low operating temperature with easy cooling requirements	Produced regulated DC power with lower energy transformation losses 
Engine structure heavy, many complex machining steps, high precision, high mechanical and thermal stress		Engine structure light, few machining steps, low precision, low mechanical and thermal stress The fuel cell stack box is the structural element and at the same time serves as enclosure to the fuel cell stack and supporting element for all Balance of Plant components	
Heavy, many very complex machining steps, high precision, high mechanical and thermal stress, complex assembly process	 	Light, few machining steps, low precision, low mechanical and thermal stress, fully automated assembly The fuel cell stack is where the fuel and air are transformed in useful energy. It does an equivalent job as of the combustion chamber and all parts associated with combustion management and containment in the ICE. The fuel cell stack equivalent in the ICE is the cylinder head and the valve train	

OTHER ENGINE SUBSYSTEMS

Fuel cell engines have a similar air system to the ICE with the addition of three parts: water separator, humidifier and the turbo electric motor. Fuel cell engines work at lower temperature and pressure, and do not require a lubrication system.

The ICE cooling loop is responsible for the engine heat load exchange and management. It is composed of many complex and hard to manufacture parts. It operates at high (110°C+) temperature which offers easy heat exchange with ambient.

The fuel cell engine cooling loop is responsible for the engine main heat load and its electronics heat load exchange and management. It is composed of simple parts but due to its low operating temperature (90°C max), it requires a large exchange area with ambient.

Fuel cell engines currently use hoses for most manifolding functions because of its low production volumes. Due to its lower operating temperature and pressure, at higher production volumes, it can make use of injected plastic manifolds that will yield lower costs and lower weight. The manifolds have a similar function on the two technologies.

Fuel cell engines have a similar wiring system compared to the ICE with the advantage of not having an ignition system.

Fuel cell engines and H2ICE utilize an identical hydrogen fuel storage system. Given the higher efficiency, fuel cell vehicles will require less storage volume for the equivalent range of distance and, as a result, save space, weight and costs.

A fuel cell engine's exhaust system can be made from plastic and contains a water separator. ICE is made from stainless steel, with complex and expensive after treatment components.

Total cost of ownership analysis

The cost of hydrogen remains the key factor impacting the viability of both technologies. The predicted hydrogen price is expected to reduce across the board in global markets with the demand for hydrogen increasing in many key industries aided by governmental initiatives.

Ballard has developed a total cost of ownership (TCO) model to analyse how the total cost of use for heavy-duty vehicles will reduce over the coming years, showing when parity with other technologies, such as internal combustion ICE engines, will be reached.

TCO CASE STUDY

For this example, we looked at a fleet of 100 long-distance (120,000km/year) 40t heavy-duty trucks in Germany. The fleet is assumed to use low-carbon hydrogen from a third-party infrastructure.

Energy cost has the largest impact for all technologies highlighting the importance of not only bringing down fuel costs but also increasing fuel efficiency. The next significant impact for fuel cell vehicles is CAPEX, namely the cost of the fuel cell and hydrogen tanks. Those are expected to significantly reduce over the coming years, with Ballard projecting 70% cost reduction in fuel cell engine cost.

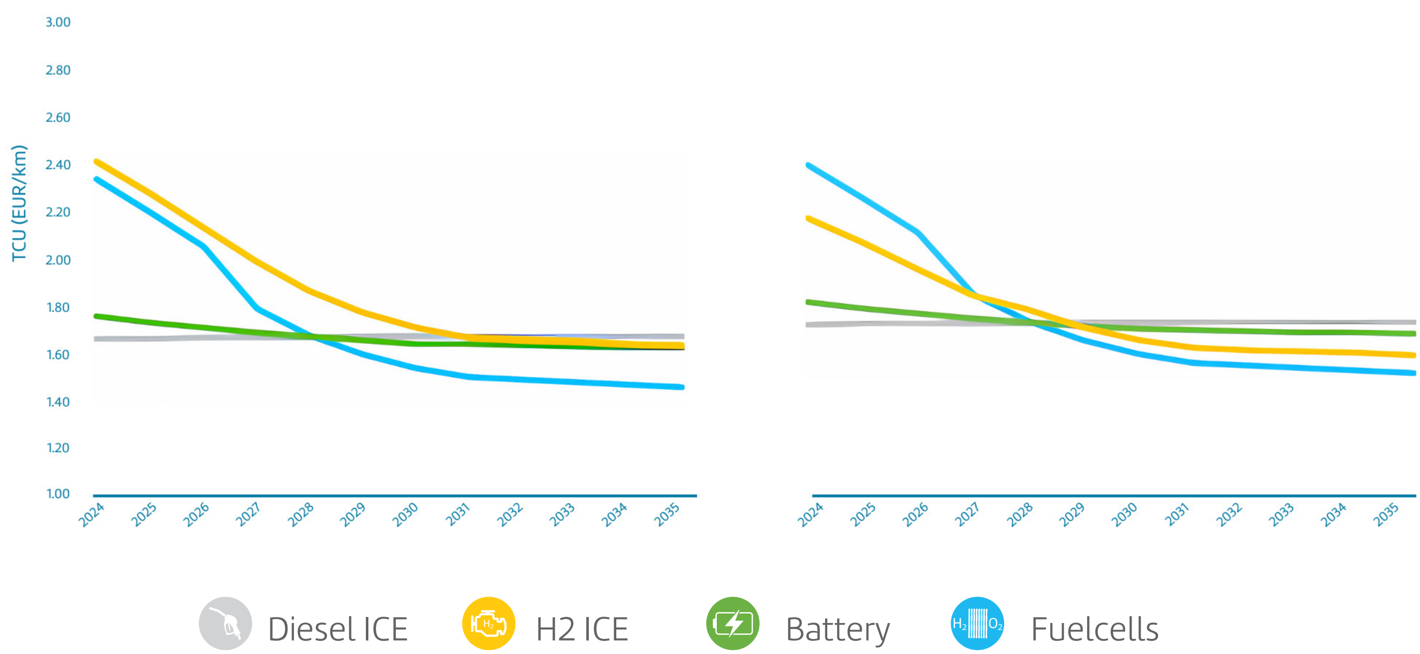
TCO ANALYSIS

Costs of supplied energy (hydrogen, diesel and electricity), fuel cell and battery hardware over time have been assumed based on latest market insights[7, 8].

Component prices for each vehicle system use current-year product costs for a fleet of 100 vehicles operating in Germany, and follow expected industry trends in commodity pricing, design and manufacture. This analysis uses Ballard's fuel cell pricing forecast and inputs from our customers, considering real product timelines and expected progresses in design and manufacture.

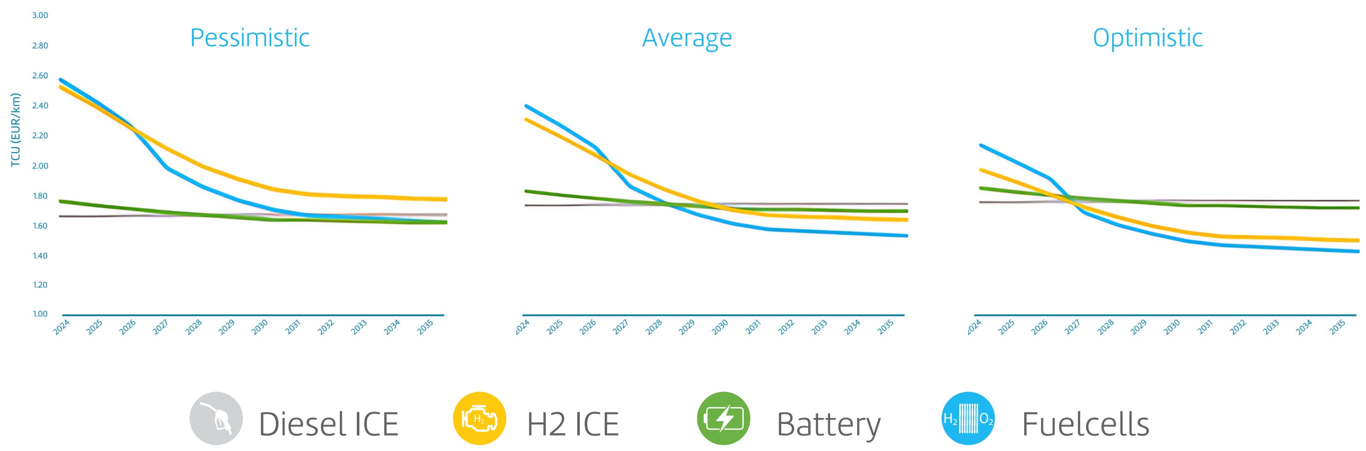
Our analysis indicates that fuel cell vehicles will reach price parity with H2ICE vehicles by 2027 assuming an average efficiency of 40% for H2ICE trucks. The primary drivers are fuel cell CAPEX, fuel efficiency and hydrogen pricing.

30% ICE-H2 Average Efficiency | **40% ICE-H2 Average Efficiency**



[7] https://www.energy.gov/eere/fuelcells/february-h2iq-hour-overview-hydrogen-internal-combustion-engine-h2ice-technologies
[8] https://theicct.org/wp-content/uploads/2023/11/ID-54-%E2%80%93-EU-HDV-TCO-paper-working-paper-28-A4-50145-v2.pdf

H_2 EUR/kg	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Optimistic	10.00	9.50	8.50	7.50	6.50	5.50	4.50	3.50	3.30	3.25	3.13	3.00
Average	15.00	14.50	13.00	11.50	10.00	8.50	7.00	5.50	5.30	5.25	5.13	5.00
Pessimistic	18.00	17.50	15.92	14.33	12.75	11.17	9.50	8.00	7.88	7.75	7.63	7.50



Due to the high cost of hydrogen and lower fuel efficiency compared to fuel cell technology, H2ICE will have a limited window of competitiveness in the heavy-duty long-haul market.

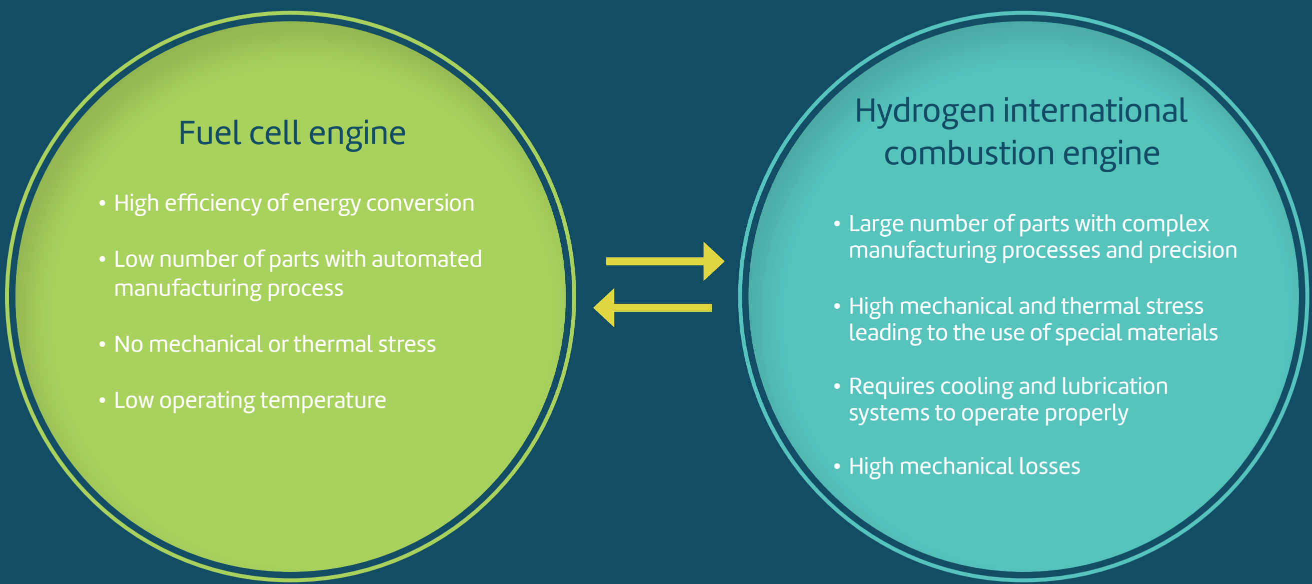
While technologies have been compared equally, it's important to note that the ICE platform currently lacks a true zero-tailpipe emission solution. The model does not additionally penalize ICE technologies with current or future-predicted emissions tolls, which is a significant consideration for long-haul or urban operators.

Conclusion

While H2ICE offers a cleaner alternative to gasoline or diesel engines, they face significant issues regarding efficiency, environmental impact, maturity, long-term economic viability, when compared with rapidly advancing technologies like electric and fuel cell vehicles.

The cost and complexity of diesel engines and H2ICE will keep increasing as emission regulations become more stringent.

Fuel cell engines are less complex with fewer parts than any ICE. Today, fuel cell engines are more expensive than ICE – including H2ICE – but as volumes scale up, fewer and more standard parts with reduced manufacturing time will drive the cost of fuel cell engines to price parity and ultimately lower cost than ICE.



Fuel cell electric vehicles will also benefit from the development and improvements in electric powertrain technology, as they share electric drive components with electric vehicle platforms. A vehicle with a fuel cell battery hybrid powertrain enables recovery and storage of valuable regenerated brake energy. This won't be possible on a H2ICE truck unless an electric motor and battery is added which will increase powertrain cost and complexity.

With lower cost at volume production, less hydrogen fuel consumption, lighter weight and no emissions and NOx, fuel cell engines are emerging as the most viable path to deliver zero-emission fleets for heavy-duty applications such as trucking where operational cost efficiency is critical.

H2ICE vehicles could offer an attractive solution for some low-volume off-road, agricultural and sport applications where fuel efficiency is less important.

The debate between H2ICE and hydrogen fuel cells in the heavy-duty vehicle sector is not just about choosing the most advanced technology, but focusing resources on the technology which has the most potential to meet – and future proof – the requirements of heavy-duty transport. The automotive industry is investing heavily in the development of battery electric technology and, to a lesser extent, fuel cells. Further development to refine H2ICE technology will divert resources from commercialising more sustainable and promising technologies such as fuel cell and battery electric vehicles.

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